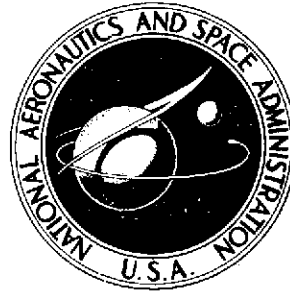


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OF AN EXPERIMENTAL COMBUSTOR SEGMENT

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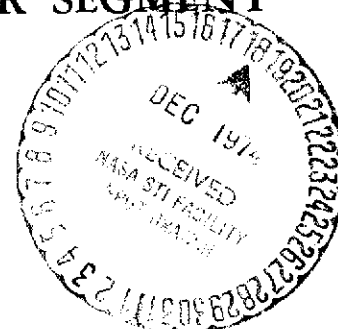
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SUMMARY

The effect of oxygen addition on the low-pressure altitude blowout limits of an experimental combustor segment was investigated. Data were obtained for two inlet-air temperatures, two inlet-airflow rates, and a constant fuel-air ratio of 0.020 with Jet A fuel with and without oxygen addition. It was shown that a significant reduction in blowout pressure could be achieved for oxygen flow rates of 8 to 16 percent by weight of the total fuel flow. The effect of reference velocities between 10 and 40 meters per second (32.8 and 131.2 ft/sec) on the blowout pressure was minimal. Reduction of the combustor pressure at blowout with oxygen addition corresponded to an increase in altitude of approximately 4.6 kilometers (15 000 ft). For an inlet temperature of 367 K (660° R) the blowout limit could be reduced with oxygen addition from 3.9 to 2.0 newtons per square centimeter (5.7 to 3 psia). For an inlet-air temperature of 311 K (560° R) with oxygen addition the blowout limit could be reduced from 8 to 4.3 newtons per square centimeter (11.8 to 6.3 psia).

INTRODUCTION

The effect of oxygen addition on the low-pressure blowout limits in an experimental aircraft gas-turbine combustor segment was investigated. Aircraft gas turbines must be capable of relighting in the event of flameout within a prescribed altitude and Mach number envelope. In the past aircraft gas-turbine engines have been designed with a slightly rich primary combustion zone which optimizes altitude relight capability. A duplex fuel nozzle is used to cover the range of fuel flows required in actual practice with the primary orifice sized for sea-level idling. Since fuel requirements at altitude are significantly reduced, it is not uncommon to have poor atomization during altitude relight. The ability to ensure relight at altitude has been made more difficult in certain

advanced aircraft because of the requirements of reducing emission levels for smoke and oxides of nitrogen (ref. 1). Smoke can be reduced by operating with a leaner primary zone and by improving atomization and mixing. Oxides of nitrogen can be reduced by lowering the flame temperature by using such techniques as making the primary combustion zone leaner and reducing the dwell time. Coupled with poor fuel atomization, design changes such as these tend to impair further altitude relight capability. Consequently, emergency relight procedures in the event of combustor flame blowout need to be considered.

Relight can often be improved by implementation of design techniques which will improve the local environment in the primary zone during light-off; however, relight cannot be achieved if conditions are not conducive to stable combustion. Relight can also be improved by using techniques such as chemical ignition or oxygen enrichment. Reference 2 reports that relight with oxygen enrichment can be accomplished at altitudes up to 6 kilometers (20 000 ft) higher than those for standard ignition with gasoline in a J-47 turbojet engine. Reference 2 indicates that a simple tube immersed in the primary zone was used for oxygen addition but does not contain sufficient information to allow determination of quantitative oxygen flow. In addition, the volatility of gasoline is considerably higher than that of jet fuels in current usage.

In general, a somewhat higher combustor pressure is required for ignition than for blowout; however, with oxygen enrichment it is possible that relight could occur in a region in which combustion is normally unstable and then permit the engine to accelerate to a stable operating region. The addition of oxygen in the primary combustion zone aids in increasing the reactivity of the mixture by increasing the flammability limits, increasing the flame velocity, and decreasing the critical quenching distance (ref. 3). Quantitatively it is very difficult to determine the effect of the various parameters on relight capability in an actual turbojet combustor because of many interrelated factors, as discussed in reference 4.

In this investigation the effect of oxygen enrichment on the blowout limits of a combustor segment was investigated experimentally with Jet A fuel with and without measured amounts of added oxygen. The combustor incorporated advanced techniques for reducing emission levels by using a lean primary zone and a short dwell time. Details of the combustor design are described in reference 5. Efficient use of the gaseous oxygen is provided by means of a dual injection system in which oxygen is admitted through ports concentric with a simplex nozzle used for liquid fuel. Blowout data were obtained for inlet-air temperatures of 311 and 367 K (560° and 660° R) by using Jet A fuel with and without oxygen addition for a fixed fuel flow.

APPARATUS AND PROCEDURE

The test combustor was mounted in the closed-duct facility described in reference 5 and shown in figure 1. Combustion air drawn from the laboratory low-pressure (37.5 N/cm^2 (40-psig)) air supply system was indirectly heated to 367 K (660° R) in a counter-flow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of ambient-temperature bypassed air. The airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet airflow were regulated by remotely controlled valves. The test combustor was exhausted to the laboratory altitude exhaust system.

The combustor inlet instrumentation station is also shown in figure 1. The inlet-air temperature was measured at the inlet with eight Chromel-Alumel thermocouples. Inlet total pressures were measured at the inlet by four stationary rakes, each consisting of three total-pressure tubes. The total-pressure tubes were connected to differential strain-gage transducers that were referenced to the static pressure obtained from static taps located at the top and bottom of the duct. To determine blowout the flame was observed through windows located 5 centimeters (2 in.) downstream of the fuel nozzle.

The combustor liner and fuel injector used in this investigation were similar to those used for combustor model 1 of reference 5 and are shown in figure 2. Oxygen at ambient temperature was injected through a series of eight evenly spaced 0.94-millimeter- (0.037-in. -) diameter holes located on a 1.75-centimeter (0.69-in.) diameter concentric with each simplex fuel injector, as shown in figure 2(b). The eight holes in each nozzle assembly were inclined 30° away from the centerline. The four simplex fuel nozzles available for this study were sized to correspond to the fuel flow requirements for sea-level idling. Each of the simplex nozzles was rated at 23 kilograms per hour (50 lb/hr) at a differential pressure of 17 newtons per square centimeter (25 psi). Airflow entering the combustor snout was admitted into the liner by means of air swirlers. The calculated primary-zone equivalence ratio of 0.70 was based on an overall fuel-air ratio of 0.020 with 50 percent recirculation from the primary holes assumed, as discussed in reference 6. The experimental combustor was selected on the basis of obtaining qualitative data. Although the combustor operated with a relatively lean primary zone, locally high gradients of fuel and air mixtures would be expected to exist, as discussed in reference 5. For future combustors a much leaner primary-zone equivalence ratio may be required to reduce nitrogen oxide emissions. In addition, the primary zone will probably have to incorporate some method to both pre-vaporize and premix the fuel. The dilution air was admitted by means of external scoops.

Tests were conducted parametrically at two weight flows (to cover a range of reference velocities) and two inlet-air temperatures to obtain inlet-temperature and

reference-velocity trends as well as altitude effects on blowout. A constant fuel-air ratio of 0.020 based on the flow of inlet air and unheated ambient Jet A fuel alone was used throughout these tests. For the fuel nozzles used this fuel-air ratio corresponds to an atomizing differential pressure of 0.5 to 2.2 newtons per square centimeter (0.8 to 3.3 psi) for airflow rates of 0.227 to 0.454 kilogram per second (0.5 to 1 lb/sec). The fuel nozzle pressure drop for altitude relight is too low to atomize the fuel effectively without assistance from the air swirlers; however, this would not be unusual, as previously mentioned in the INTRODUCTION.

Blowout data were obtained by visually observing the flame through sapphire windows located downstream of the fuel nozzles (fig. 2(a)). Combustor pressure was reduced until visual flameout was observed, and the combustor pressure at blowout was recorded. The combustor reference velocity at blowout was based on a maximum cross-sectional area of 465 square centimeters (72 in.²). For blowout tests with oxygen enrichment the oxygen flow rate was metered through calibrated rotameters. The gaseous oxygen was at ambient temperature. As a check on the blowout data at relight a point based on one of the blowout conditions was obtained. The spark energy for the igniter was 12 joules with a sparking rate of 2.5 sparks per second.

For reference purposes the altitude relight requirements for a subsonic and an advanced supersonic aircraft turbine engine are presented in table I. In this program the minimum available air temperature was 311 K (560° R). It would be expected that the lower inlet-air temperature required for simulation of condition 1 would make relight more difficult than at 311 K (560° R). The inlet-air temperature for simulation of condition 2 is somewhat less severe than the 367 K (660° R) level used in this program.

RESULTS AND DISCUSSION

The blowout characteristics of Jet A fuel with oxygen enrichment were compared with the blowout limits of Jet A fuel alone for a constant fuel-air ratio of 0.020. It would normally be expected that the combustor pressure at relight would be somewhat higher than the blowout pressure; however, for relight, it is required that an optimum ignition system be defined. In the experimental combustor segment in which this study was conducted no attempt was made to determine the optimum spark energy or position; therefore, blowout was selected as a measure of the relight region. Blowout was obtained for a parametric variation of two inlet-air temperatures and two airflow rates. A single relight point was obtained by increasing the inlet-air temperature at a fixed pressure.

The specific purposes of this investigation was to extend the blowout limits, to determine the degree of reduction of pressure at blowout with oxygen enrichment, and to determine qualitatively the oxygen flow rates required. Oxygen flow rates were varied

from 2 to 275 percent by weight of the total fuel flow at marginal operating pressures for fixed inlet-air temperature and airflow rate. At low oxygen flow rates flickering and unstable burning were observed, whereas, at higher oxygen flow rates the flickering ceased and a stable flame was observed. As a result of these visual observations it was concluded that a stable flame could be obtained with a relatively low oxygen flow rate. An oxygen flow rate of 0.756 gram per second (6 lb/hr) was chosen and was held constant for all tests. Based on the percent by weight of the total fuel flow for an overall fuel-air ratio of 0.020, the oxygen flow rate was 8 percent for an airflow rate of 0.454 kilogram per second (1 lb/sec) and 16 percent for an airflow rate of 0.272 kilogram per second (1/2 lb/sec).

Blowout data for Jet A fuel injection with and without the addition of oxygen are presented in figure 3 for two values of inlet-air temperature. As shown in figure 3(a), for an inlet temperature of 367 K (660° R) the blowout limit could be reduced with oxygen addition from 3.9 to 2.0 newtons per square centimeter (5.7 to 3 psia). For an inlet-air temperature of 311 K (560° R) (fig. 3(b)) the blowout limit could be reduced with oxygen addition from 8 to 4.3 newtons per square centimeter (11.8 to 6.3 psia). The decrease in the pressure at blowout with oxygen enrichment corresponds to an increase in altitude of approximately 4.6 kilometers (15 000 ft).

As shown in figure 3, the reference velocity varied as much as 4 to 1, that is, from 10 to 40 meters per second (32.8 to 131.2 ft/sec) as the operating conditions were changed. The pressure at blowout was relatively insensitive to variation in reference velocity; however, the percentage of oxygen enrichment varied from 16 to 8 percent as the reference velocity varied from 10 to 40 meters per second (32.8 to 131.2 ft/sec).

The effect of inlet-air temperature was quite pronounced. The data from figure 3 are cross plotted in figure 4 for a constant reference velocity of 21.3 meters per second (70 ft/sec). As shown in figure 4, blowout limits were severely affected by the lower inlet-air temperature. Differences in the blowout limits for variation in inlet-air temperature would be expected because of the effect of inlet parameters on the chemical kinetics.

Vaporization and mixing are also very important because a combustible mixture must be present before the fuel can be burned. Jet A fuel has a low volatility (boiling point range from 447 to 547 K (804° to 984° R) at 10 N/cm² (14.7 psia)), has an average molecular weight of 164, and is paraffinic in nature; therefore, at stoichiometry approximately 1.2 percent of the Jet A fuel is vaporized. At an inlet-air temperature of 367 K (660° R) and an absolute pressure of 4.1 newtons per square centimeter (6 psia), approximately 4.4 percent of the fuel could possibly have been vaporized at equilibrium, and the mixture was combustible. As the inlet-air temperature was decreased to 311 K (560° R) at an absolute pressure of 4.1 newtons per square centimeter (6 psia), the vapor pressure of the fuel was lowered and approximately 0.2 percent of the fuel could have been vaporized at equilibrium, so that the mixture was below the lean flammability

limit. Therefore, as the inlet-air temperature is reduced, relight problems become severe for low-volatility fuels such as Jet A.

In these tests the fuel was injected into the combustor at ambient temperature. In actual practice fuel is used in a heat exchanger as the coolant for the lubrication system. In the event of combustor blowout at altitude the fuel would still be hot; consequently, the high inlet fuel temperature would aid vaporization rather than hinder it as did the low temperature of the unheated fuel in these tests.

Comparison of the data from figure 4 with the relight conditions as listed in table I indicates that for the supersonic condition (2) it should be possible to light this combustor without oxygen enrichment at an inlet-air temperature of 389 K (700° R); however, a loss of airspeed would severely affect relight. For the subsonic condition (1) a major improvement in relight capability would be required to light the combustor at an inlet-air temperature of 244 K (400° R) even though enrichment would markedly improve the blowout limit. It should be feasible to improve the environment in the primary zone by some method such as variable geometry in conjunction with oxygen enrichment and thereby improve altitude relight reliability. Consideration of the engine operating envelope would be required in order to provide relight reliability for any aircraft gas-turbine application.

Also shown in figure 4 is a relight point that was taken with oxygen enrichment at a pressure of 2 newtons per square centimeter (3 psia) with an airflow rate of 0.227 kilogram per second (1/2 lb/sec) and an oxygen flow of 16 percent by weight of the total fuel flow. It was not possible to relight at an inlet-air temperature of 367 K (660° R); however, when the inlet-air temperature was increased from 367 to 372 K (660° to 670° R), ignition was achieved, which indicated that the fuel vaporization process is quite critical even with the addition of oxygen.

Since highly localized regions are controlling during relight, it would be difficult to account for the actual sequence of mechanisms which influences relight to the greatest extent. Possibilities include not only kinetics and fuel vaporization but also improved mixing due to the addition of gaseous jets around the fuel nozzle. No attempt was made in this program to optimize the oxygen injection system.

SUMMARY OF RESULTS

The effect of oxygen enrichment on the low-pressure blowout limits in an experimental combustor segment using Jet A fuel was investigated. Data were obtained for two inlet-air temperatures and a constant fuel-air ratio of 0.020. The following results were obtained:

1. A significant improvement in blowout limit with oxygen enrichment was demonstrated for a relatively small weight of oxygen, 8 to 16 percent by weight of the total fuel flow.
2. Reduction of the combustor pressure at blowout by oxygen addition corresponded to an increase in altitude of approximately 4.6 kilometers (15 000 ft).
 - a. For an inlet temperature of 367 K (660⁰ R) the blowout limit could be reduced with oxygen addition from 3.9 to 2.0 newtons per square centimeter (5.7 to 3 psia).
 - b. For an inlet-air temperature of 311 K (560⁰ R) the blowout limit could be reduced with oxygen addition from 8 to 4.3 newtons per square centimeter (11.8 to 6.3 psia).
3. The effect of reference velocities between 10 and 40 meters per second (32.8 and 131.2 ft/sec) on the blowout pressure was minimal.

Lewis Research Center,
 National Aeronautics and Space Administration,
 Cleveland, Ohio, September 17, 1974,
 501-24.

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TABLE I. - ALTITUDE RELIGHT CONDITIONS

[Reference velocity, 21.3 m/sec (70 ft/sec).]

Aircraft	Altitude		Flight Mach number	Inlet-air temperature		Inlet pressure	
	m	ft		K	°R	N/cm ²	psia
Subsonic (condition 1)	10 668	35 000	0.8	244	440	3.5	5.2
Supersonic (condition 2)	19 812	65 000	2.0	389	700	4.1	6

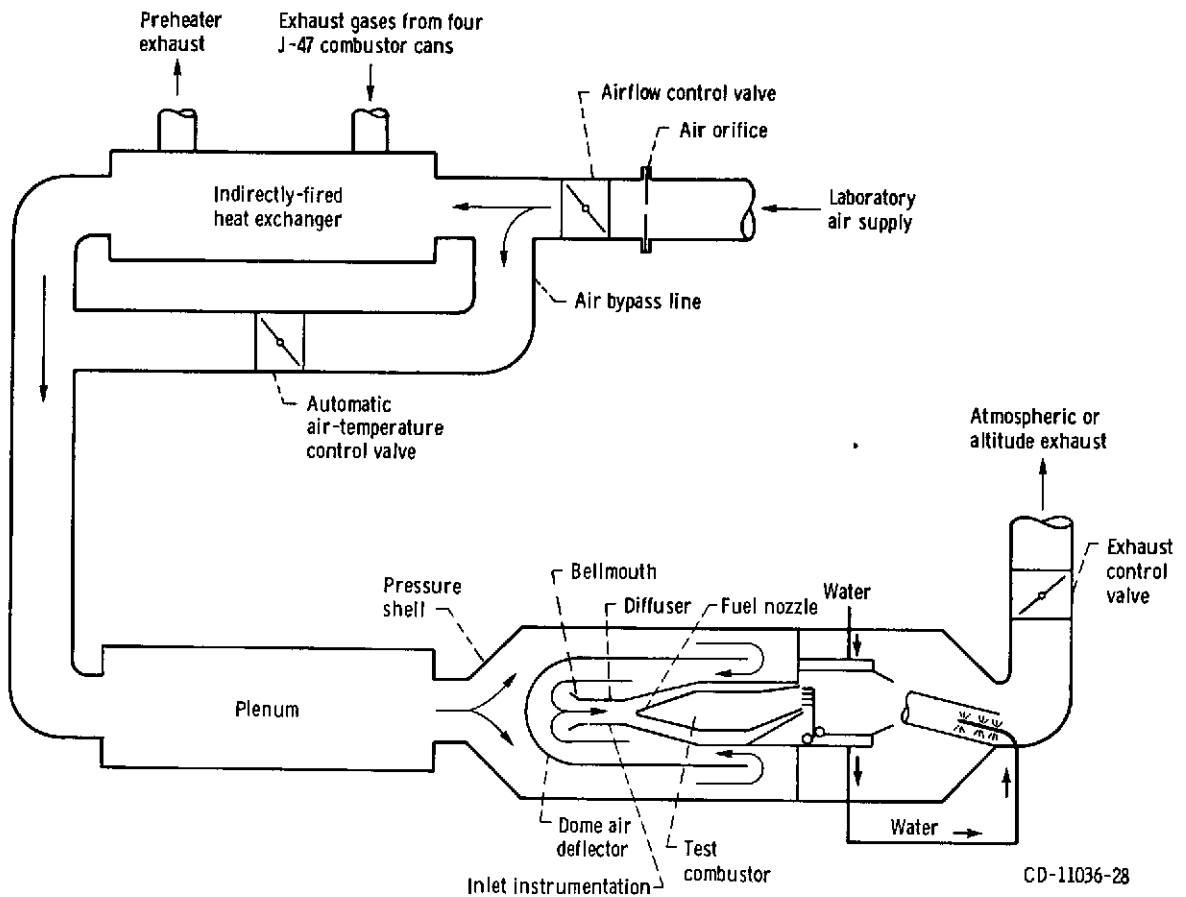
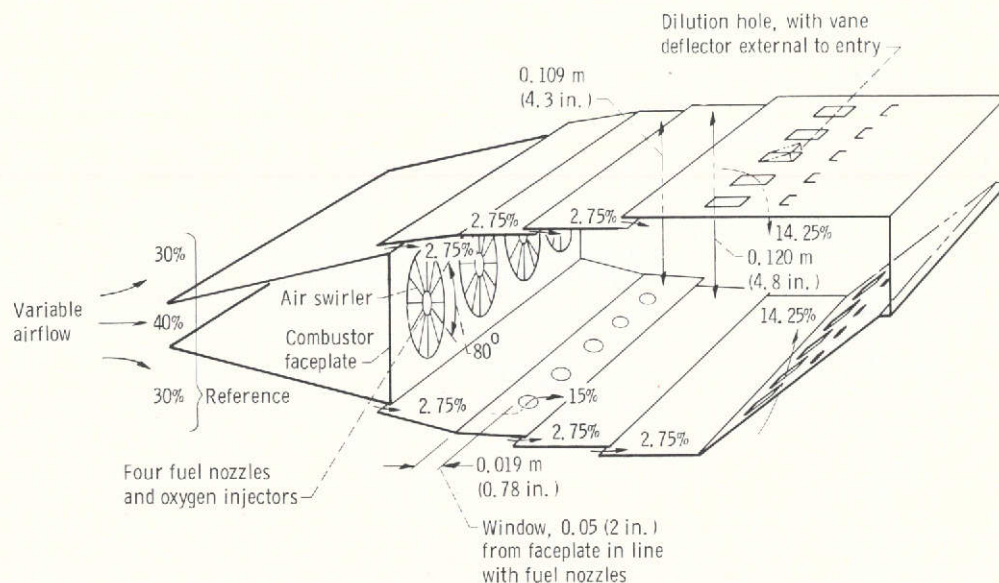
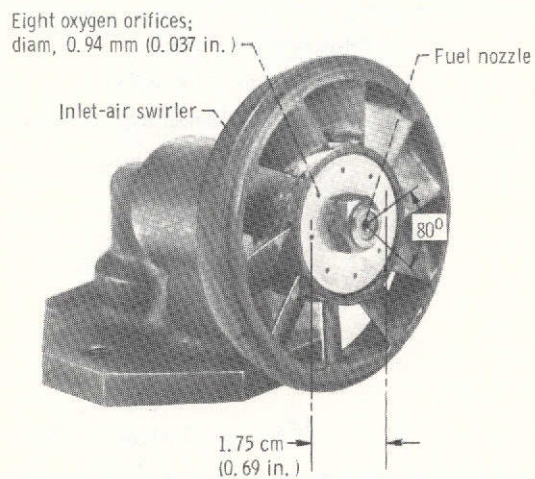


Figure 1. - Test facility and auxiliary equipment.



(a) Combustor liner.



(b) Fuel and oxygen injector.

Figure 2. - Schematic of combustor liner and fuel and oxygen injector. Combustor width, 0.31 meter (12 in.); combustor length, 0.32 meter (12.5 in.); maximum combustor housing height, 0.15 meter (6 in.).

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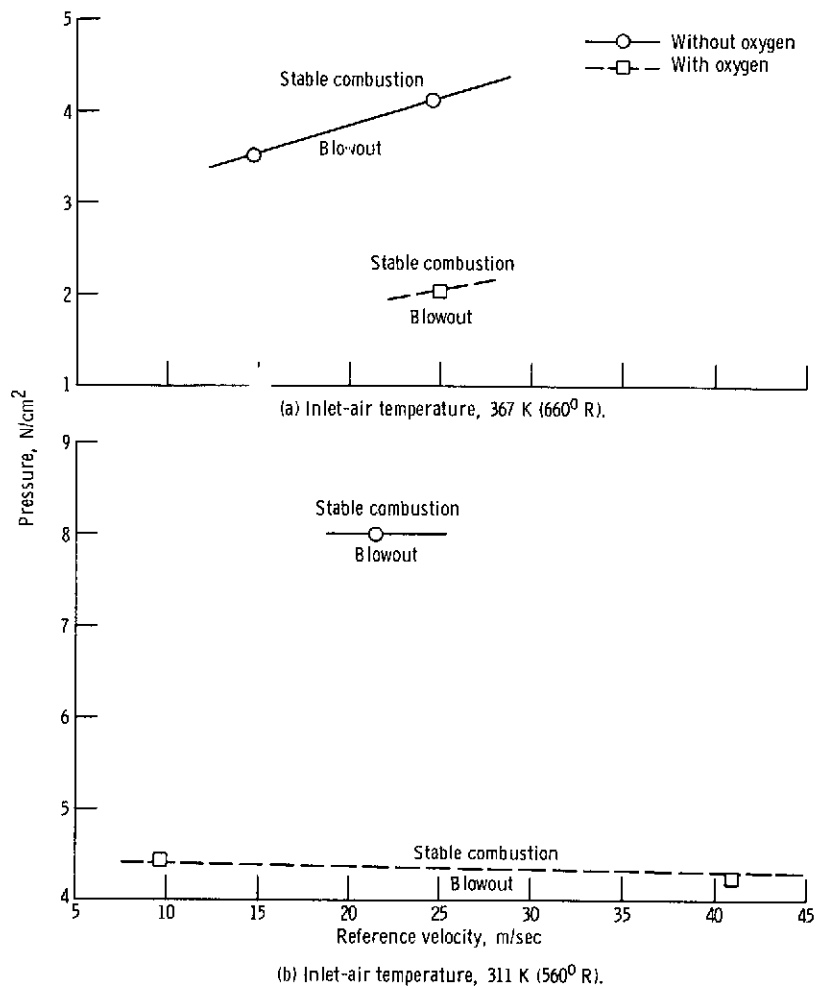


Figure 3. - Blowout limits of Jet A fuel with and without oxygen enrichment for overall fuel-air ratio of 0.020.

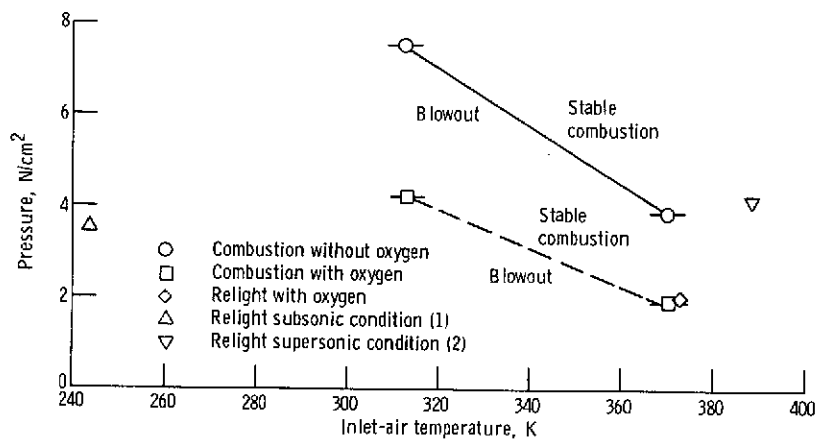


Figure 4. - Effect of inlet-air temperature on blowout limits of Jet A fuel with and without oxygen addition for overall fuel-air ratio of 0.020.